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WORKING CONDITIONS OF THE INTERNAL BOUNDARY LAYER BLEED OF AN EXTERNAL SUPERSONIC COMPRESSION AIR INTAKE

J.Leynaert

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The theory of operation of an external supersonic airscoop, using a bleed with internal boundary layer, is discussed from the viewpoint of flow separation and re-attachment at oblique and curved inlet shocks. An attempt is made to apply experimental data for optimizing the efficiency of air intakes at three-dimensional flow. Schematized layouts are given for strategic location of the boundary-layer bleed at the inlet of the subsonic diffuser, for preventing separation of flow during change-over from supersonic to subsonic regime, in flights of Mach-2 supersonic transports.

Author

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J. Leynaert

The structure of the flow in an external supersonic compression air intake, of negligible body slope and provided with a bleed with an internal boundary layer placed at the theoretical origin of the subsonic diffuser, does not actually correspond to the classical scheme of a supersonic compression terminated by a straight shock. In fact, the effective shock is oblique and curved inward and, at the level of the bleed, a limited transonic expansion takes place.

The boundary of the flow above the bleed consists of an isobaric mixing layer; the mass flow from the bleed is concentrated in a jet, formed at the point of re-attachment of this mixing layer to the leading edge of the diffuser.

An investigation of the equilibrium conditions at the point of re-attachment of the flow shows that the mass rate of flow of the bleed is determined as a function of the engine output. As soon as this output diminishes, the mass flow rate of the bleed increases, causing the bleed to play the role of an automatic bypass, bypassing the entrance of the air-scoop in subcritical regime. The deformation of the entrance shock curvature and the adaptation of the internal transonic expansion result in the fact that the efficiency remains con-

* Numbers in the margin indicate pagination in the original foreign text.

stant within the zone where this phenomenon might become effective. The extent of this zone depends on the maximum mass flow permitted by the evacuation circuit of the secondary air. Under normal operating conditions, any deviation in control of this mass flow will have only a local effect and will not influence the flow at the end of the diffuser.

A detailed description of these phenomena gives an explanation for the development of the overall characteristics of the air intake and facilitates the search for a solution, yielding a flow of optimum efficiency and uniformity at the exit from the diffuser.

1. Introduction

Despite many years of studies and practical supersonic flight tests, the problem of airscoops is far from being solved. In fact, only the supersonic /2 portion of the flow is easy to cover by exact computations in simple two-dimensional or axisymmetric forms. This is no longer the case for three-dimensional forms that frequently become of interest. To define the transonic and subsonic portion, empirical laws are the only data available, obtained from laborious experimental studies (Bibl.1, 2, 3). For example, this is the case for the form of an internal boundary layer bleed, located at the base of the terminal shock of an air intake with external supersonic compression. Comparative experiments on removal of the boundary layer by suction, using a perforated continuous wall or capture in bleeds with or without Pitot effect, have shown that this latter arrangement is the most favorable at present (Bibl.4). Studies made at the ONERA (National Aerospace Research and Development Administration) for the case of a flight Mach number of 2, have confirmed and further elaborated this viewpoint (Bibl.5). At the same time, this research gave a better view over the operating mechanism of an internal bleed (Bibl.6). This analysis will be presented below, for the case of a two-dimensional air intake.

2. General Description of the Flow in an Air Intake

The air intake to be discussed is of the classical type (Fig.1a). A profiled ramp ensures a progressive compression of the supersonic flow whose waves are focused on the rim of the body, at the adaptation Mach number, so as to avoid any "additive" drag. The internal profile of the body has a slope of the rim more shallow than the local slope of the incident flow and an accentuated curvature, so as to minimize the external drag. A subsonic diffuser is used for decelerating the flow up to the inlet plane of the compressor.

The boundary-layer bleed is placed at the inlet of the diffuser, in the form of a large orifice extending the profile of supersonic compression. In this region, the flow undergoes an abrupt deviation and a considerable increase in pressure, passing from the supersonic to the subsonic regime. The removal by suction of a certain mass flow by the bleed prevents separation of the boundary layer which would otherwise occur.

An examination of the flow in Fig.1a shows that the classical configuration of a supersonic compression, terminated by a straight shock, is abandoned here. In fact, the inlet shock is an oblique shock curved toward the diffuser at the approach to the internal bleed. Within the cavity of the bleed, there is a zone of dead water, at a pressure p_b. Depending on the individual case, this pressure is either below or above that of the incident flow, which results either in an expansion or in a local compression near the origin of the bleed D.

The schematic sketch in Fig.1a refers to the case of identical pressures, i.e., to the case without deviation.

The oblique inlet shock, on encountering the isobaric boundary of the dead water zone, results in an expansion at its impact point producing a deviation of the main flow which, along the boundary, retains the same pressure p_b, i.e., practically the same Mach number M_T, since the isentropic stagnation pressure loss through the oblique shock is relatively low.

The internal supersonic expansion diminishes progressively with distance from the bleed and is unable to extend up to the body in whose vicinity, in this case, the flow remains subsonic. Here, an incurved sonic line limits the supersonic region. A straight shock (T) terminates this expansion immediately ahead of the downstream edge of the bleed. The intensity of this shock diminishes progressively with distance from the mixing line and finally vanishes along the sonic line.

Downstream of the base of the shock, the boundary of the subsonic flow /3
abruptly assumes a steep curvature, so as to compensate, by centrifugal effect, the pressure gradient between the dead water zone and the main flow recompressed by the shock. The flow then becomes re-attached to the wall of the subsonic diffuser. The curvature of the inlet shock and the intensity of the transonic shock depend on the geometry of the system. These conditions can be defined in such a manner that the combination of the two shocks, along each streamline, produces more or less the same original pressure loss. At the end of the diffuser, this will result in a uniform profile of stagnation pressure and velocity. The total efficiency of the configuration reaches 0.94 at M = 2.

The mass flow, taken in by the dead water, in almost its entity is concentrated in a jet attached to the trailing edge of the bleed. A minimum mass flow rate must be ensured so as to avoid a separation of flow in the diffuser and to increase the efficiency by removal of the incident boundary layer, which is greatly thickened along the boundary of the wake. The local pattern of the streamlines is shown in Fig.1b.

Let (P) be the streamline ending at the stagnation point A. The portion of the flow, located below this line, is able to overcome the local compression created about the point A, and is able to flow normally within the diffuser. The slower fluid particles, flowing on top of this line, are backed up into the cavity of the bleed. Within this trap, the particles expand to form a narrow jet which might locally reach supersonic velocities and will then lose its kinetic energy under the effect of viscosity and possible shock waves. The flow in the vicinity of the point A will be discussed in more detail later in the text during discussion of the operating mechanism of the bleed.

3. Operating Principle of the Bleed with Internal Boundary Layer

Observations have demonstrated the existence of a domain that can be designated as the normal operating range of the air intake, with the following features: Control of boundary layer removal by the bleed does not change the removed mass flow (secondary mass flow) and influences only the pressure p_b of the wake. This control also has no influence on the pressure recovery of the main flow. Aside from this, the bleed may play the role of an automatic bypass for compensating the fluctuations of the main mass flow.

These two aspects of bleed operation will be studied in sequence, followed by a definition of the limits of their field of application, i.e., the domain of normal operation.

3.1 Boundary Layer Control by the Bleed

Let us investigate the processes taking place on progressively reducing the critical cross section A_{cb} of the secondary mass flow, without changing the control of the main mass flow (critical cross section A_c = const). The evolution of the flow is shown schematically in Sketches 2.1 and 2.2 of Fig.2.

Experimentally, the following facts are obtained:

The pressure p_b rises, but the main mass flow and the secondary mass flow remain unchanged.

In the bleed, the supersonic portion of the jet (j) is reduced under /4 the effect of an increase in p_b.

The mixing layer is slightly deformed in the sense of the compression of the exterior flow; however, its length and the mean Mach number of the exterior flow vary relatively little, so that the profile of the stagnation pressures upstream of the re-attachment at point A is preserved.

In turn, this compression results in

a slight deviation at D;

a straightening of the inlet shock (E), which becomes more pronounced at the approach to the bleed;

a reduction of the transonic domain and of the Mach number of internal expansion;

correlatively, a decrease in intensity of the terminal shock (T).

Overall, there is a compensation of the effects of (E) and (T), so that the main flow remains invariant. Specifically, the profile of the stagnation pressures downstream of (T) as well as the pressure recovery remain unchanged.

To explain the invariance of the secondary mass flow in this adjustment zone of A_{cb}, let us return to the sketch of the flow in the vicinity of the point A (Fig.1b).

A priori, only three elements contributing to the determination of the parting streamline (P) can be considered in this diagram: the profile of stagnation pressures of the incident flow and the pressure fields on either side of the point A, in the diffuser and in the wake. In fact, the presence of a supersonic domain in the jet (J) results in a protection of the stagnation point A and of the surrounding subsonic region from any variations in p_b; the pressure of the wake p_b is then only a secondary factor of the equilibrium in question. Thus, the division of the flow depends practically only on two other factors, namely, on the pressure field at the inlet of the diffuser and on the profile of the upstream stagnation pressures in the mixing zone and the nonviscous flow which it limits. However, it was found that these elements are invariant for a limited evolution of the pressure p_b. If the secondary mass flow is relatively minor, the parting line (P) is the streamline of the mixing layer of the isentropic stagnation pressure p_A; since this pressure, at the stagnation point A, is determined by the downstream pressure field, the parting line (P) and thus also the secondary mass flow are retained.

This particular scheme clearly indicates the dominant concept in modern theories of the re-attachment of an isobaric mixing layer to a wall (Bibl.7); however, here the phenomena are more complex because of the presence of the shocks (E) and (T) as well as of a subsonic downstream flow. In addition, the properties cover mass flow rates that are greater than those of the incident mixing layer, a topic that goes beyond the scope of these particular theories.

3.2 Compensation of Fluctuations in the Main Mass Flow

It is of interest to define what would happen if, without changing the control of boundary removal by the bleed (constant critical cross section A_{cb}), the rate of the main flow (critical cross section A_c) would be varied.

Let us again consider the case of the Sketch 2.1 in Fig.2, for which the /5 cross section A_{cb} is most divergent and let us assume that A_c is diminished. This will result in the Sketch 2.3. Since the Mach number in the diffuser is reduced, the pressure at the diffuser inlet will be higher. The new parting line (P') will thus be located at the point indicated in Fig.2.3 with respect to (P). The mass flow, passing through the bleed, will then increase.

Since the volume flow rate of the bleed is kept constant (fixed A_{cb}), the pressure in the bleed p_b increases proportionally to the mass rate of flow.

The increase in the pressure p_b, for the main flow, results in a new configuration which, to within the intake flow rate, is qualitatively identical with the old configuration of the preceding case (Fig.2.2), obtained for the same pressure level p_b. The phenomenon of compensation of the intensity of the shocks (E) and (T) preserves the profile of the stagnation pressures downstream of (T).

In normal operation, the initial parting line (P) is located outside the mixing layer proper. The profile of the stagnation pressures of the nonviscous flow is then practically uniform, so that the elimination of a supplementary portion of the mass flow will leave the efficiency almost unchanged.

Actually, the reduction in the main mass flow, other conditions being equal, will lead to a corresponding increase in the bleed mass flow rate and in the wake pressure, while the total pressure recovery will remain constant.

This clearly indicates that the bleed may play the role of an automatic bypass, for compensating fluctuations in the main mass flow.

Obviously, this function has relatively narrow limits (of the order of 4%

of the mass flow rate, as will be demonstrated below); however, if a control device for the critical cross section A_{cb} of the bleed is available, this particular function of bypass can be greatly extended.

In fact, let us return to the last case (Sketch 2.3 in Fig.2) and let us assume that the main mass flow rate is to be further diminished ($A_{c4} < A_{c3}$), retaining a constant bleed pressure ($p_{b4} = p_{b3}$), so as to benefit from the same general pattern of the main flow at practically the same pressure recovery; for this, it is sufficient to diverge A_{cb} in proportion with the additional mass flow removed in the dead water by a decrease in the main mass flow rate.

A comparison of the Sketches 2.3 and 2.4 shows that a new parting line (P") is established under the effect of the higher ram pressures in the diffuser, while otherwise the flow remains unchanged since the pressure of the bleed had been restored by the divergence of A_{cb}.

Until now, we used the hypothesis that the suction removal by the bleed was controlled by its critical cross section A_{cb}. Actually, in some cases it /6 is possible to use a more flexible system, for example that of ejecting the secondary mass flow to the rear of the engine, through a slot downstream of the throat of a converging-diverging nozzle. In this case, the discharge conditions are ruled by the engine operating regime which, at the same time, defines the intake mass flow rate; these conditions have partly the same effect as an automatic adaptation of the critical discharge cross section A_{cb} (Bibl.8 - 9).

3.3 Operating Limits

Above, we described the operating principle of the air intake within its adaptation domain; we will now define its limits.

3.3.1 Limits of the Secondary Mass Flow Rate, at Constant p_b

It has been demonstrated above that the general pattern of the flow was defined by the pressure p_b in the bleed. Particularly, if a variable secondary mass flow is discharged at a constant pressure p_b, the flow pattern will remain unchanged. This property is maintained only between two limits:

Toward high mass flow passing through the bleed, it is probable that a separation of flow will finally appear near the rim of the diffuser; however, in our particular case, the tests made up to 20% of the mass flow rate through the bleed had not reached this limit.

Toward low mass flows, when the incident mixing layer is only in part sucked into the bleed, a progressive degradation of the stagnation pressure profile takes place in the diffuser along the wall, leading to a reduction in efficiency.

The thickness of this mixing layer increases almost linearly, as a function of the length of the bleed. For an extended bleed, having a length (for example) equal to 75% of the inlet height of the air intake, the mass flow to be removed for optimizing the efficiency will reach 6.5% of the total mass flow rate. However, a decrease in this rate of flow to below this value will have only a minor effect, as stated above.

Before a substantial separation of flow will appear in the diffuser, the secondary mass flow rates will have to be extremely low, of the order of 1%.

3.3.2 Limits of p_b

The domain of values of p_b acceptable for proper operation has two limits:

Toward low bleed pressures (Fig.3a), the internal supersonic re-acceleration which manifests itself in a first expansion at the point of flow separation D and in a second expansion at the impact point of (E) on the free boundary, will lead to an increasingly more intense shock (T), while (E) will tend to become stationary. The phenomenon of compensation of the shocks (E) and (T) no longer intervenes here. The resultant loss in efficiency is quite progressive and leads to a greater interaction of the shock (T) with the lateral boundary layers of the air /7 intake.

Toward high bleed pressures (Fig.3b), the inlet shock, after having straightened, is rammed upstream of the rim of the body. The supersonic expansion at the base of this shock on the free boundary is reduced considerably and is replaced by a succession of small transonic expansion zones, each followed by their own shock T_1, T_2, ... When the shock (E), emerging from the inlet, encounters the focused beam of the upstream supersonic compression, a slip line is generated. As soon as this slip line enters the air intake, pumping will appear (J.Ferri).

It should be recalled here that such pumping usually has a frequency related to the time required by the perturbations to propagate from the inlet to the obstacle that controls the main mass flow rate at the end of the diffuser. However, for certain specific configurations, it happens that the aerodynamic constriction, formed between the body and the fluid boundary of the bleed, will play the same role as the exit constriction. In that case, the pumping will increase greatly in frequency, at reduced amplitude. Thus, cases of pumping at 2500 cps have been observed in the wind tunnel, for an aircraft mockup at a scale of about 1/10. Originally, the configuration in question was considered stable, since a strioscopic observation showed no specific phenomenon; later, this type of pumping was detected in short-response high-speed pressure measurements.

4. Overall Characteristics

It is useful to assemble the operating elements of the above-described air intake in a diagram,giving the general development of the overall characteristics.

In Fig.4, the results were plotted as a function of the coefficient of mass flow rate of the main flow ϵ, the total pressure recovery of the air intake η, the coefficient of rate of flow of the bleed ϵ_b, and its efficiency η_b, which latter is equal to the pressure of the wake relative to p_{t0}, as could be demonstrated (the jet of the bleed loses its entire kinetic energy in the dead water). A definition of these quantities is given in Fig.4.

For simplification, we plotted the results for only two values of the critical cross section A_{cb} of the mass flow rate of the bleed, which was a priori assumed as fixed and located in the normal operating range of the air intake.

Let us first take the case of the smallest cross section A_{cb}. The element BC of the efficiency curve η represents the compensation range of a quasi-constant efficiency of the main mass flow by the bleed mass flow rate, as demonstrated by the curve giving ϵ_b as a function of ϵ and having a slope of -1.

From A to B, the internal supersonic expansion leads to a high Mach number of the shock (T), so that the pressure recovery cannot take place.

From C to D, the shock is rammed upstream of the inlet (subcritical re- /8
gime), and the main mass flow rate decreases more rapidly than the secondary mass flow rate can increase.

The efficiency of the bleed η_b obeys the same law as ϵ_b, since - because of A_{cb} being given - η_b is proportional to ϵ_b.

Let us now assign the upper value to A_{cb}. At the points A'B'C'D', which are at the same bleed pressures p_b as the preceding points ABCD, the flow at the homologous points is similar, except that for each point, the bleed mass flow rate is increased proportionally to A_{cb} while the main mass flow rate is decreased by the same amount. This leads to a displacement of the curve (η, ϵ) toward the left.

Considering the operation of the rocket engine unit, it seems that the optimum solution for an adaptation of the air intake to the variable conditions of the mass flow rate would be to constantly retain positions such as the points BB'. These points are characterized by high efficiency, zero deviation of the mass flow rate upstream of the inlet (zero "additive" drag), and some safety margin relative to constant pumping. The points correspond to similar internal flow patterns, of the same pressure p_b. To maintain this regime in cruising flight, it is sufficient to ensure the invariance of this pressure (or, expressed more accurately, the invariance of the ratio of this pressure to the ambient pressure).

5. Influence of Geometric Parameters on the Overall Characteristics

Some data should be given on the influence of the geometric parameters of the air intake. Let us return to the general flow pattern (Fig.1). No theoretical method for calculating the flow referring to conditions at given limits are in existence (shape of the walls and main and secondary mass flow rates); similarly, no methods are available for predicting the conditions at which the subcritical regime would intervene. However, the prime obstacle encountered in tests on air intakes of this type, specifically if an attempt is made to reduce the drag of the external fairing is the fact that, in certain cases, the expulsion of the shock and the resultant pumping occur even before the bleed has been able to start functioning properly. The performance of the air intake will then be rather poor.

In view of the lack of any theory for predicting such phenomena, a few experimental data on a specific configuration should be given. The following elements have been defined as having a tendency to provoke a premature expulsion of the shock:

A displacement toward the body of the leading edge of the diffuser which, against all expectations, does not improve the capture of the secondary mass flow because of the fact that the bleed continues operating in the same pattern as before, up to considerable divergences; simultaneously, a blocking effect occurs, which has the tendency of repelling the shock (E) in an upstream direction.

Too low an initial divergence of the diffuser.

Too strong a curvature of the body of the bleed.

Insufficient length of the bleed.

Obviously, this holds specifically for a given supersonic compression ahead of the inlet. The length of the compression ramp also plays an important role /9 in these phenomena.

Finally, the form of the upstream supersonic compression itself may have an influence on the internal configuration. Thus, by giving a certain curvature to the shock at the head of the compression beam, by suitably profiling the ramp, an accentuation of the curvature of the shock (E) could be obtained for a given geometry of the diffuser, which would have the result to shift the pumping limit backward and to produce a more uniform flow at the end of the diffuser.

Naturally, all these results are interdependent, and an optimum solution can be obtained only after a long series of experiments.

6. Conclusions

Above, we gave a qualitative description of the functioning of a certain type of air intake, characterized by low external fairing drag, optimum efficiency in a wide variation range of engine output, and possibility of automatic adaptation of the mass flow rate by using a bleed with internal boundary layer.

In view of the nonexistence of any theoretical computation method, the development of such an air intake, for a specific application, required a long experimental study which yielded a few orienting concepts for later investigations.

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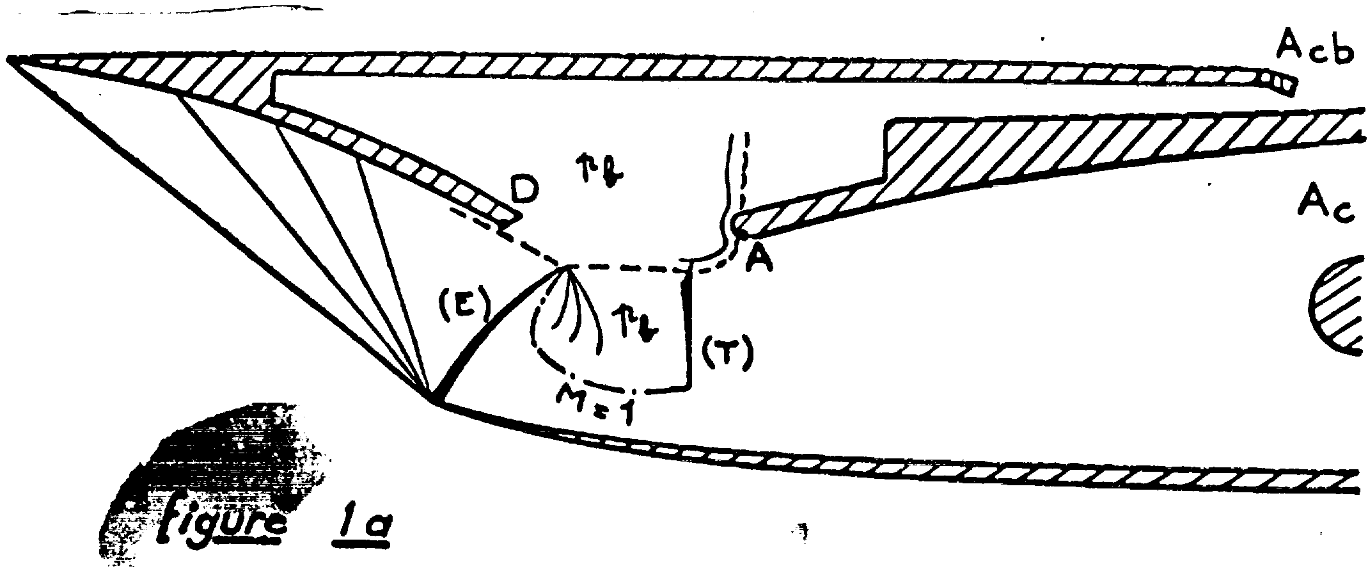
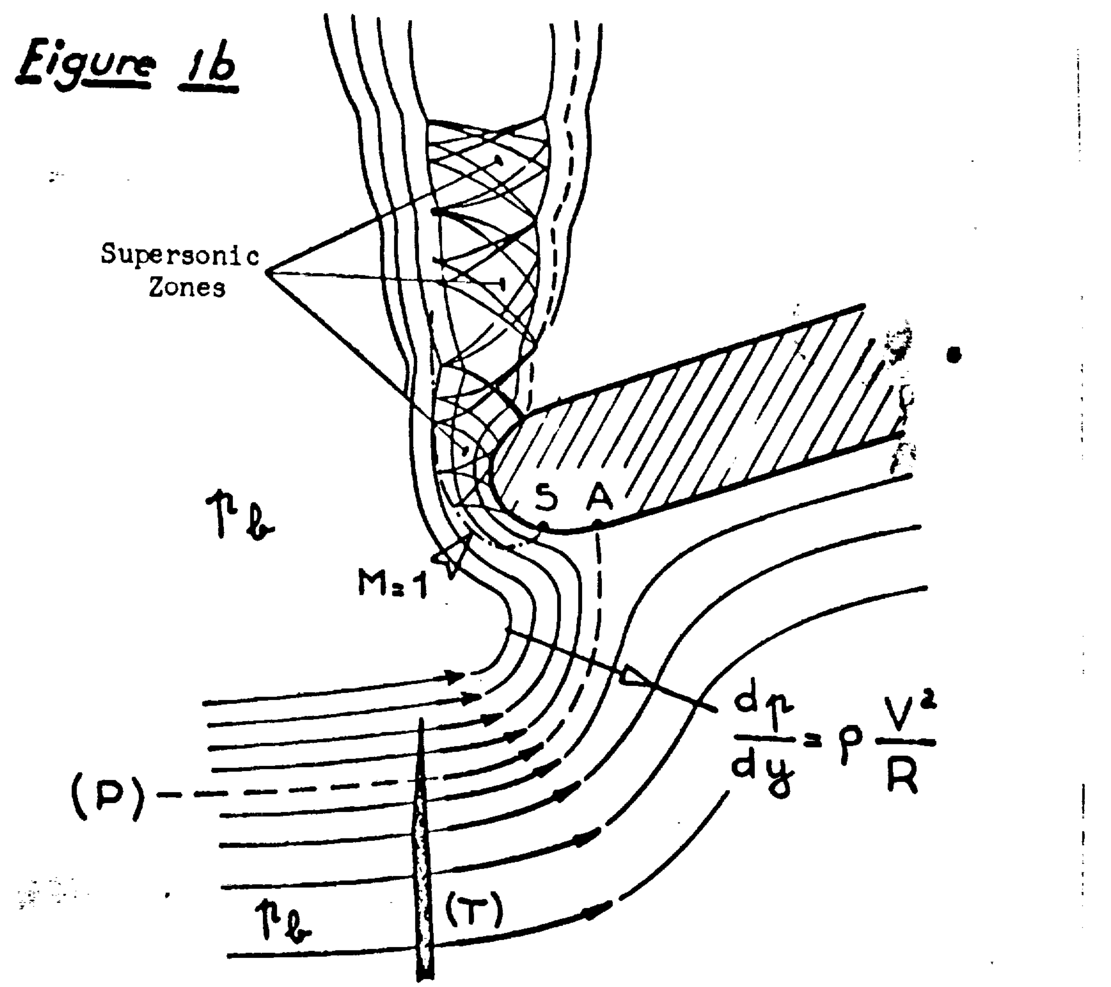
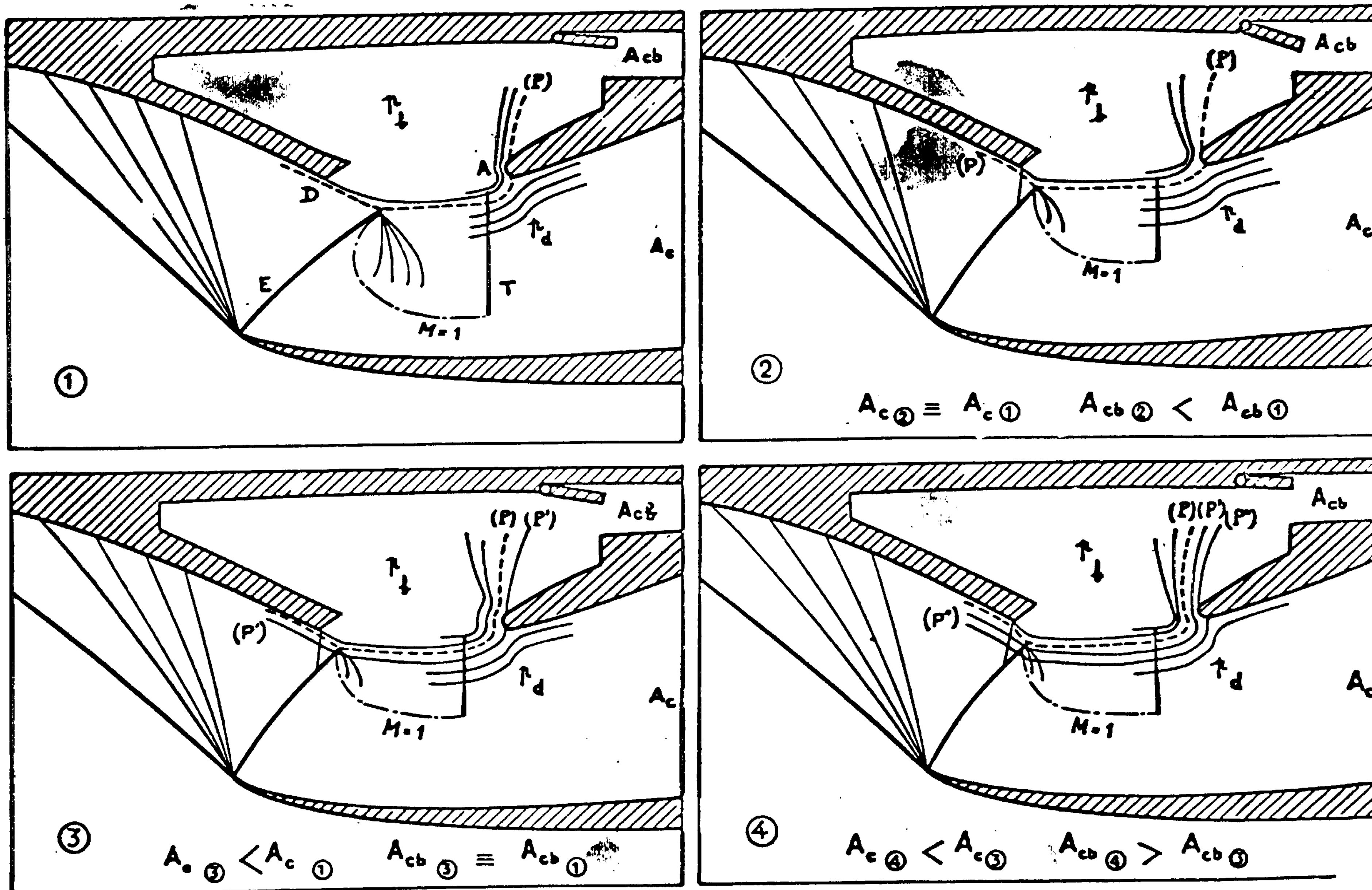




Figs.1a and 1b General Description of the Main Flow and the Bleed-Mass Flow



①② Control of the critical bleed section ①③ Effect of the automatic bypass ③④ Effect of the controlled bypass

Fig.2

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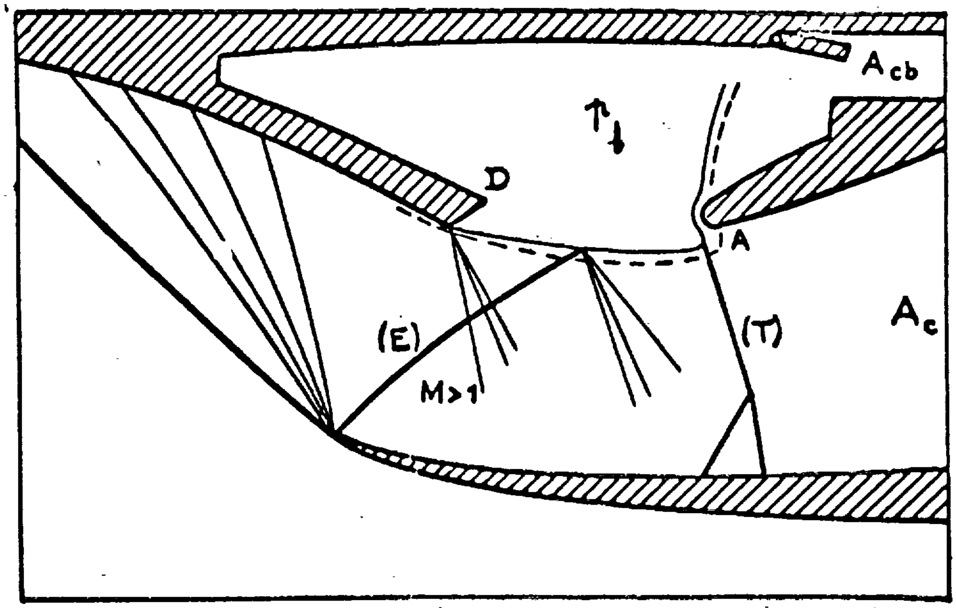

Fig.3a Supercritical Regime

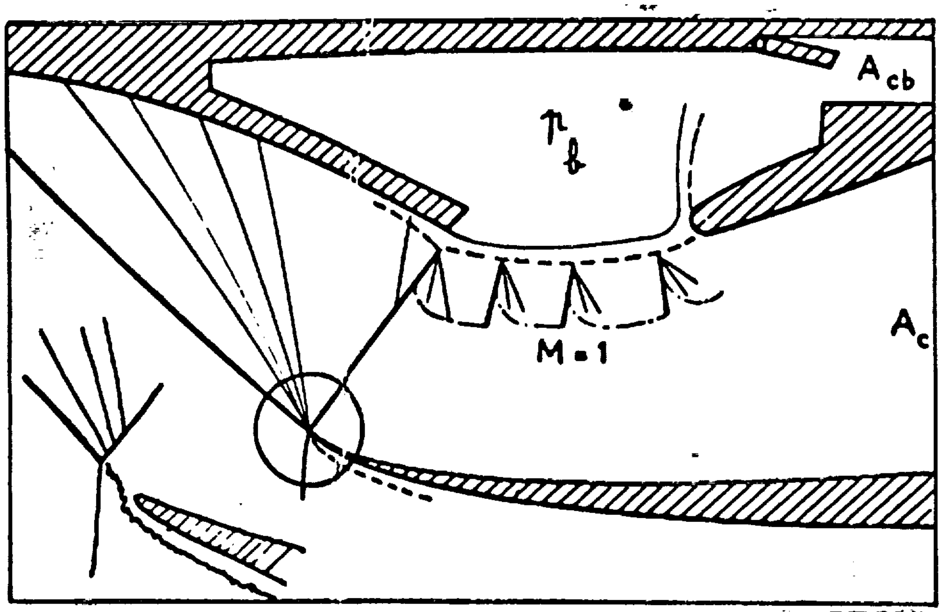

Fig.3b Critical Regime and Pumping Limit

Fig.3 Limits of Variation in p_b in the Domain of Correct Operation

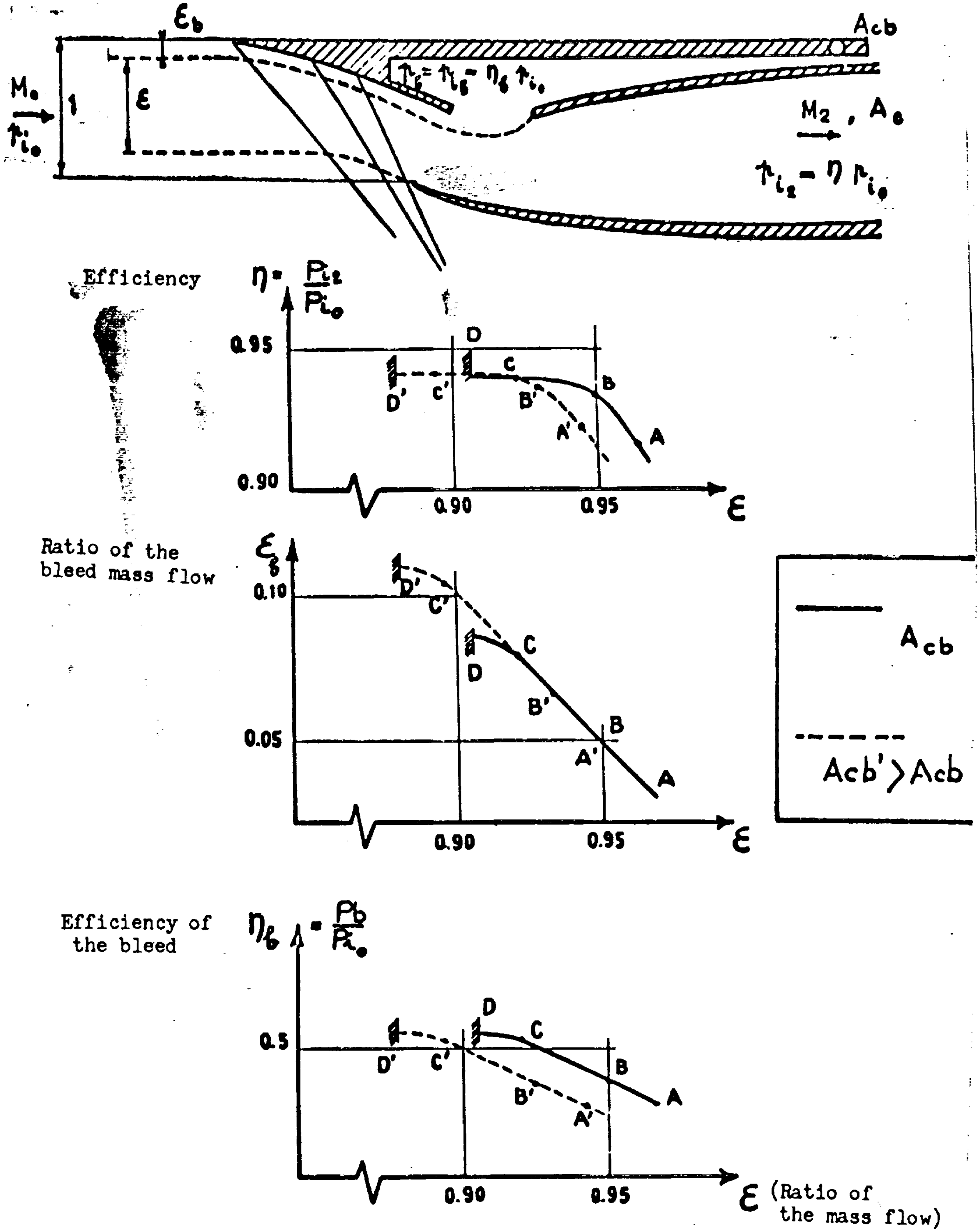

Fig.4 Overall characteristics curves